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Abstract

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May 1988 Annual Report on ONR Grant N00014-87-K-0396
Spontaneous Force Optical Traps
Principal Investigator Carl E. Wieman

We have spent the past year obtaining preliminary data on the
behavior of laser cooled atoms, and modifying the apparatus in
response to what we have learned. The two major components of
the experimental hardware are the vacuum system and the diode
lasers. We rather quickly learned that the very slow atoms we
were producing were dramatically affected by background gas
collisions even at rather low pressures. Thus it was necessary
to construct a vacuum system which was capable of pressures in
the 10^{-10} torr range. With this system we have seen preliminary
indications of atom trapping based on optical pumping. The
performance of this trap was found to be extremely sensitive to
magnetic fields. To such an extent it proved necessary to replace
the ion pump we were using, because of the stray magnetic fields
associated with it. We are now in the process of obtaining a
cryopump which will provide similarly low pressures but without
stray fields.

We have also been developing the necessary laser technology.
By locking the frequency of the diode lasers to optical cavities,
which are in turn locked to the atomic transitions, we have
produced a laser source of exceptional performance. It is
tuneable, it has a bandwidth of much less than one megahertz, a
long term stability of a fraction of a megahertz, and extremely
low amplitude noise. In addition to all this, it is both
inexpensive and compact.

These lasers have proven very useful for cooling atoms. As
discussed in the attached preprint, we have used them to cool a
large number of cesium atoms from room temperature to about 0.1
mK. This work has been accepted for publication and will be
appearing in JOSA B any day now. Very recently Phillips' group
at NBS has reported unexpectedly low temperatures in optical
molasses. Because it is essential to understand molassesy if one
is to make optical traps, we are now carrying out a detailed
study of its behavior. These studies have the advantage over
what has been done in sodium that the excited state hyperfine
splitting is much larger and hence the interpretation of our
results is not clouded by questions about the possible coherence
of the different hyperfine states. We are in the process of
determining how the behavior of optical molasses depends on the
light intensity, frequency, and polarization in the different
beams. At the present time we are obtaining very interesting
results which show that this system is rather complicated and new
theories will be necessary to explain it.

We have also built and tested a polarization modulator which
allows us to produce a standing wave which does not lead to
coherence between different m levels of the ground state in
cesium. This will be used for making an optical trap which
relies on optical pumping between different hyperfine states. We
have done some theoretical analysis of this trap (which indicated
the need for such a modulator) and it looks quite promising.

Production of a very cold atomic vapor using diode laser cooling

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ABSTRACT

We have used the light from diode lasers to strongly damp the motion of atoms in a cesium vapor. We have been able to contain more than 10^7 atoms for 0.2 sec and cool them to a temperature of 100^{+100}_{-30} μK in this viscous photon medium (so called "optical molasses").

In the past few years there has been a flurry of work demonstrating new ways to use laser light to control the positions and velocities of atoms.[1,2] However, nearly all of this work involves rather elaborate and expensive technology. We have been working to achieve these capabilities using technology that is simple enough to be practical for use in a wide variety of atomic and molecular physics experiments. In a previous paper[3] we presented a simple and inexpensive way to stop a beam of cesium atoms using frequency chirped diode lasers. In this paper we present the implementation of "optical molasses" using diode lasers, and discuss improved results on atom stopping. The cooled vapor produced in this work was colder and significantly denser than has been previously obtained with sodium in optical molasses[2] produced by a dye laser.

The idea of cooling an atomic sample using counterpropagating laser beams was originally proposed by Hansch and Schalow[4] in 1975. They pointed out that, if an atom sees counterpropagating laser beams which are tuned slightly below a transition frequency, the Doppler shift will cause the atom to preferentially absorb photons moving opposite to its velocity. The momentum imparted by these photons will cause the atom to slow down and thus be cooled. In 1984 Chu et al.[2] demonstrated this idea in a vapor of sodium atoms, and coined the name "optical molasses." They sent a beam of relatively slow moving sodium atoms into a region where six laser beams intersected in a cross. These beams cooled the atoms to a temperature, $T - h\gamma/4k$, which is the theoretically predicted[2] minimum temperature one can achieve when exciting a resonance line of width γ. Also, they showed that the photons produced a highly viscous medium which confined the atoms for a fraction of a second before they could diffuse out of it. This production of free atoms which are

far colder than anything previously obtainable opens up a rich new area for experiments; e.g., using these atoms for ultrahigh resolution spectroscopy or studying the interactions of these very cold atoms with surfaces or other atoms.

Such experiments are far more practical if diode lasers can be used to cool the atoms. Tuneable diode lasers have a number of important advantages over the dye lasers which were used exclusively in the early work on laser cooling. The most striking feature, of course, is their much lower cost. Other advantages which are well known are that they are simpler to use; since there are no optical elements to get misaligned and dirty, it is easy to rapidly change the output frequency, and they have good intensity stability. An advantage which is not well known is that it is quite easy to obtain diode laser linewidths of much less than 1 MHz. A free running diode laser has a typical linewidth of 30 MHz, but Hollberg and coworkers[5] have recently shown that a small amount of optical feedback from a Fabry-Perot interferometer will lock the laser frequency to that of the interferometer, and can reduce the linewidth by more than a factor of 1000. In this experiment we utilized this technique.

To produce ultracold cesium atoms we first started with a thermal atomic beam. These atoms were slowed to a few hundred cm/sec by a beam of counterpropagating resonant laser light. The slow moving atoms then drifted into a region where intersecting laser beams, which were tuned slightly below the center of the atomic resonance, formed the optical molasses. This light cooled the atoms and held them for an extended period of time. We studied the atoms by observing their fluorescence while in this region.

A schematic of the apparatus for this experiment is shown in Fig. 1. A beam of cesium effused from an oven into one end of a vacuum chamber and the frequency chirped laser beam entered from the opposite end. This initial slowing portion of the experiment was identical to that discussed in Ref. 3, except that the stopping laser was locked to an interferometer cavity, and the stopping distance had been extended to 90 cm. To lock the laser, a small portion of the output beam was sent into a 5 cm confocal cavity which was a few cm from the laser. The cavity was tilted slightly so that the beam entered at an angle relative to the cavity axis. On the order of 1% of the laser power returned to it and caused its frequency to lock to that of the external cavity. If the free running laser frequency was within about 500 MHz of the cavity resonance, the optical feedback would pull laser frequency to the cavity resonance. This allowed us to coarsely tune the laser frequency using temperature and current in the usual manner, and then do fine tuning by changing the resonant frequency of the cavity using a piezoelectric transducer to translate one of the mirrors.

The stopping laser drove the $6S_{F=4}$ to $6P_{3/2}$ $F=5$ resonance transition. A second laser, which was not locked to a cavity, was tuned to the $6S$ $F=3$ to $6P_{3/2}$ $F=4$ transition to insure that atoms were not lost to the F=3 ground state. The frequencies of these two lasers were swept from about 500 MHz below the respective transition frequencies to within a few MHz of the transition. Then the stopping laser frequency was quickly (≈ 30 μsec) shifted away from the resonant frequency. The frequency of the stopping laser, just before shifting, determined the final velocity of the atoms as they entered the molasses. The F=3 state depletion laser remained at the same frequency it had at the end of the ramp and thus insured that the F=3 state also remained

depleted in the molasses. The frequencies of both lasers were monitored using small cesium saturated absorption spectrometers.

The optical molasses was produced by light from a third laser which was also locked to a cavity. The output of this laser passed through an attenuator and an optical isolator and was then split into three beams, each containing about 0.5 mW of power, which intersected each other at right angles. The intersection region was slightly less than 1 cm in diameter and overlapped the cesium beam. The three beams were reflected back on themselves by dielectric mirrors. A small part of the output from the "molasses laser" was used to obtain a saturated absorption spectrum in a cesium cell. This spectrum provided an error signal which was fed back to the cavity to hold the laser frequency on the red side of the F=4 to F=5 transition. These three lasers were sufficient to cool the atoms. However, to obtain higher densities in the molasses by multiple loading, we used a fourth (unstabilized) laser as described below. A silicon photodiode monitored the fluorescence from the molasses region.

The cooling chirp slowed the atoms in the cesium beam to several hundred cm/sec or less. We found that using a cavity-locked stabilized laser significantly improved the efficiency of this process. The number of stopped atoms was about 2.5 times larger with a stabilized laser than it was with an unstabilized laser, as was used in our previous work. The number of fast background atoms was correspondingly decreased relative to the unstabilized case. Apparently some of the laser frequency fluctuations were large enough to cause the frequency to briefly change faster than the maximum allowable ramp rate. If this happens, some of the atoms are not decelerated enough to stay in resonance with the laser, and they are no longer slowed. In the

present work we obtained about 5×10^6 stopped atoms/cm^{-} and there were very few fast moving background atoms until a few milliseconds after the stopping chirp was finished. The narrower laser linewidth also allowed much better control over the final velocity of the atoms.

Once the atoms were slowed to low velocity they could be caught by the molasses. The fluorescence from the molasses region showed a rapid rise during the stopping laser frequency chirp followed by a long decay indicating a very slow departure of the atoms. The behavior of the atoms in the optical molasses depended quite critically on the velocity they had as they entered the molasses region. To obtain reproducible results the end of the frequency ramp had to remain constant to within about 1 MHz (1 MHz corresponds to $v \approx$ 100 cm/sec). If the atoms were moving too slowly they did not penetrate into the molasses, but instead they piled up on the surface and quickly diffused away. Best results were obtained when they had a final velocity of several hundred cm/sec so they penetrated the entire molasses region. This also produced a denser sample since a larger volume of stopped atoms went into the molasses. In this situation the fluorescence signal from the molasses region would continue to rise for several milliseconds after the stopping laser was switched off. If the atomic velocity was increased further the atoms would fly right through the molasses.

Once the atoms were stuck in the molasses they diffused out very slowly. This is illustrated in the plot of the fluorescence as a function of time in Fig. 2. As one would expect, the diffusion time was a sensitive function of loading velocity, alignment, and molasses laser power and frequency. The longest 1/e decay time we observed was 0.2 sec. We found that the conditions for maximum decay time were: intensity about one half the saturation

intensity, frequency detuning between 0.5 and 1 natural line width, and loading velocity of a few 100 cm/sec. These values are in reasonable agreement with what is predicted for these parameters using the results in Ref. 6.

Because the atoms remained in the molasses for 20 times longer than the time for a stopping chirp (10 msec), one could obtain much higher densities by repeated loading of the molasses. However, this required a fourth laser to provide the F-3 state depletion in the molasses while another batch of atoms was being stopped. In the left hand side of Fig. 2 one can see the effects of loading eight bunches. The dots show the fluorescence level after each additional bunch was loaded. After eight bunches the loading was stopped and there was a slow decay of the fluorescence. By using multiple loading we were able to increase the number of atoms in the molasses by more than a factor of 10. From the amount of fluorescence we estimate the maximum number of atoms we contained in the molasses was about 5×10^7. This was bright enough, when observed with an infrared viewer, that it could be seen in a well-lit room.

We determined the temperature of this vapor by measuring the spread of the atoms in the dark, as was done in Ref. 2. After the atoms had been in the molasses for about 25 msec, the molasses laser was quickly switched off. A brief time later the light was turned back on and the decrease in the fluorescence was measured. In Fig. 3 we show the fluorescence as a function of the time the light was off. After more than 35 msec with the light off, the subsequent fluorescence was dramatically less (falling off rapidly with longer times without light). We believe this was due to the gravitational acceleration of the atoms. We fitted the points in Fig. 3 with the calculated curve for the expansion of a uniform sphere of atoms with a Maxwell-Boltzmann velocity distribution. This curve will be changed somewhat

by the gravitational acceleration, but this effect appears to be small for times less than 35 msec. From this fit we find the temperature to be 100^{+100}_{-30} μK. There is considerable uncertainty in this measurement because the decay was a strong function of the distribution of the atoms, and we could see that the distribution was only vaguely spherical and could change somewhat from one batch to the next. Nevertheless, this value is in good agreement with the predicted[2] limit, $h\gamma/4k = 125$ μK for this transition, and is colder than any cooled atoms or ions previously reported. At this temperature the rms velocity for these atoms is only about 15 cm/sec.

We have achieved an extremely cold and moderately dense atomic vapor by cooling atoms using light from inexpensive diode lasers. With the light on, this vapor will remain for a fraction of a second, and with the light off the atomic motion is largely determined by gravitational acceleration. The technology required to achieve this remarkable behavior is simple enough that such atoms could be produced routinely to be used for precision spectroscopy or collision studies.

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Figure captions

Fig. 1. Schematic of the apparatus. The third molasses beam, which
was perpindicular to the other two, is not shown. FP1 and 2
are the Fabry-Perot locking cavities. The saturated
absorption spectrometers are labeled SAS1 and 2.

Fig. 2. Real time trace of the flourescence. The black dots on the
left side show the level after each new bunch of atoms was
loaded. After eight bunches the loading was stopped, and
the right hand side shows the subsequent decay of the
fluorescence as the atoms diffuse away.

Fig. 3. The pluses show the fraction of the initial fluorescence
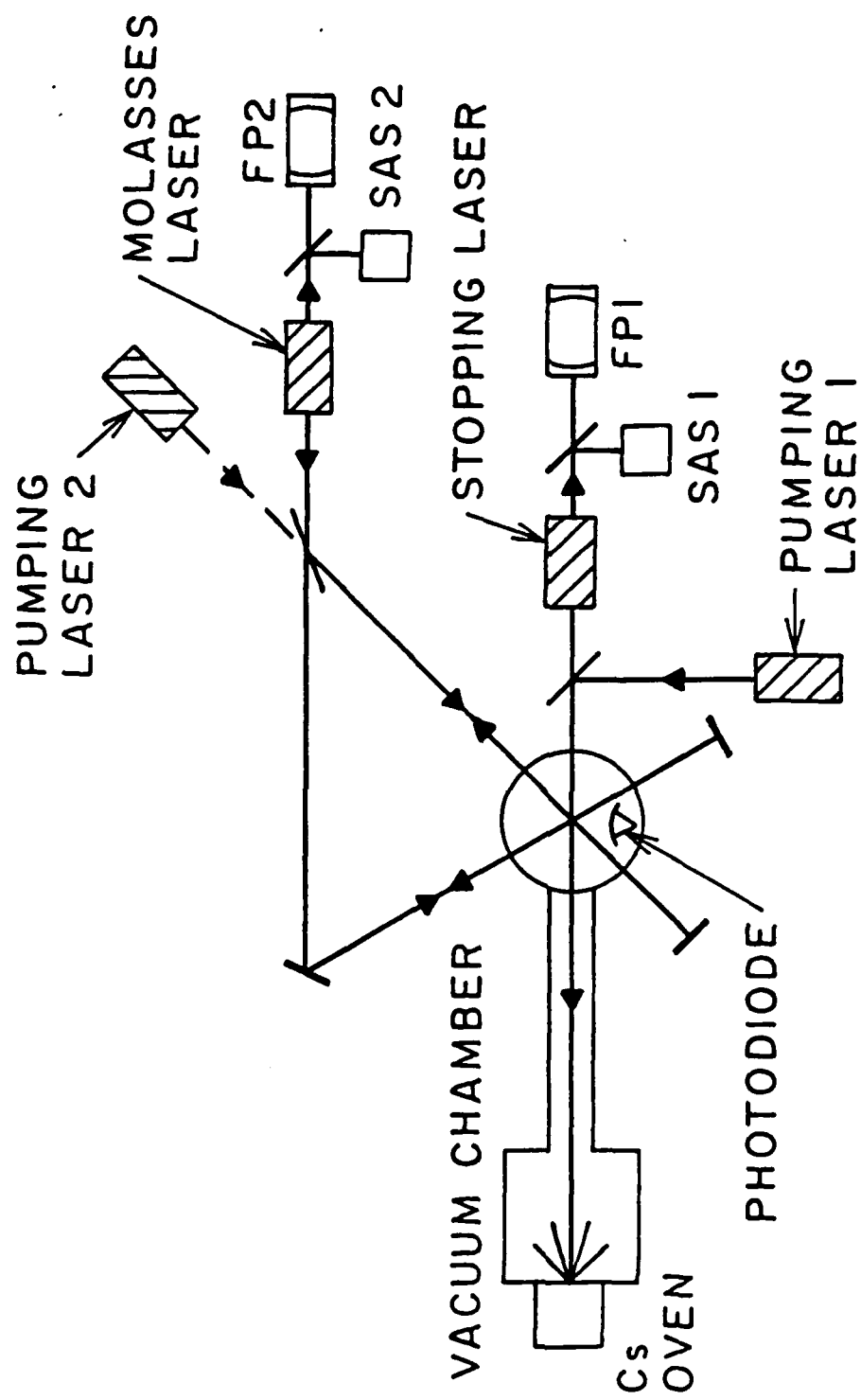which remained after the molasses laser was blocked for the
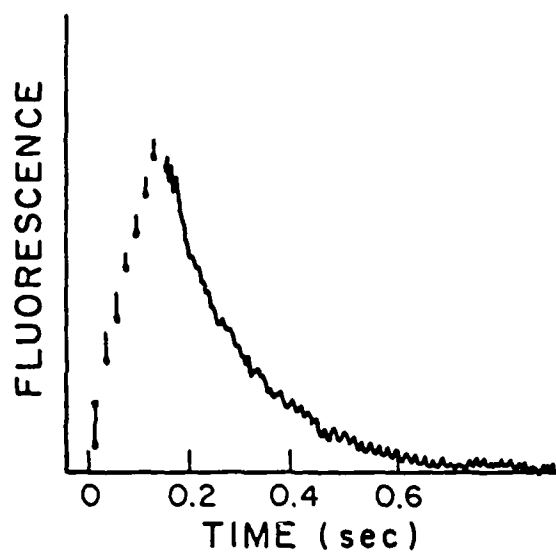time intervals shown. The solid line is the theoretical
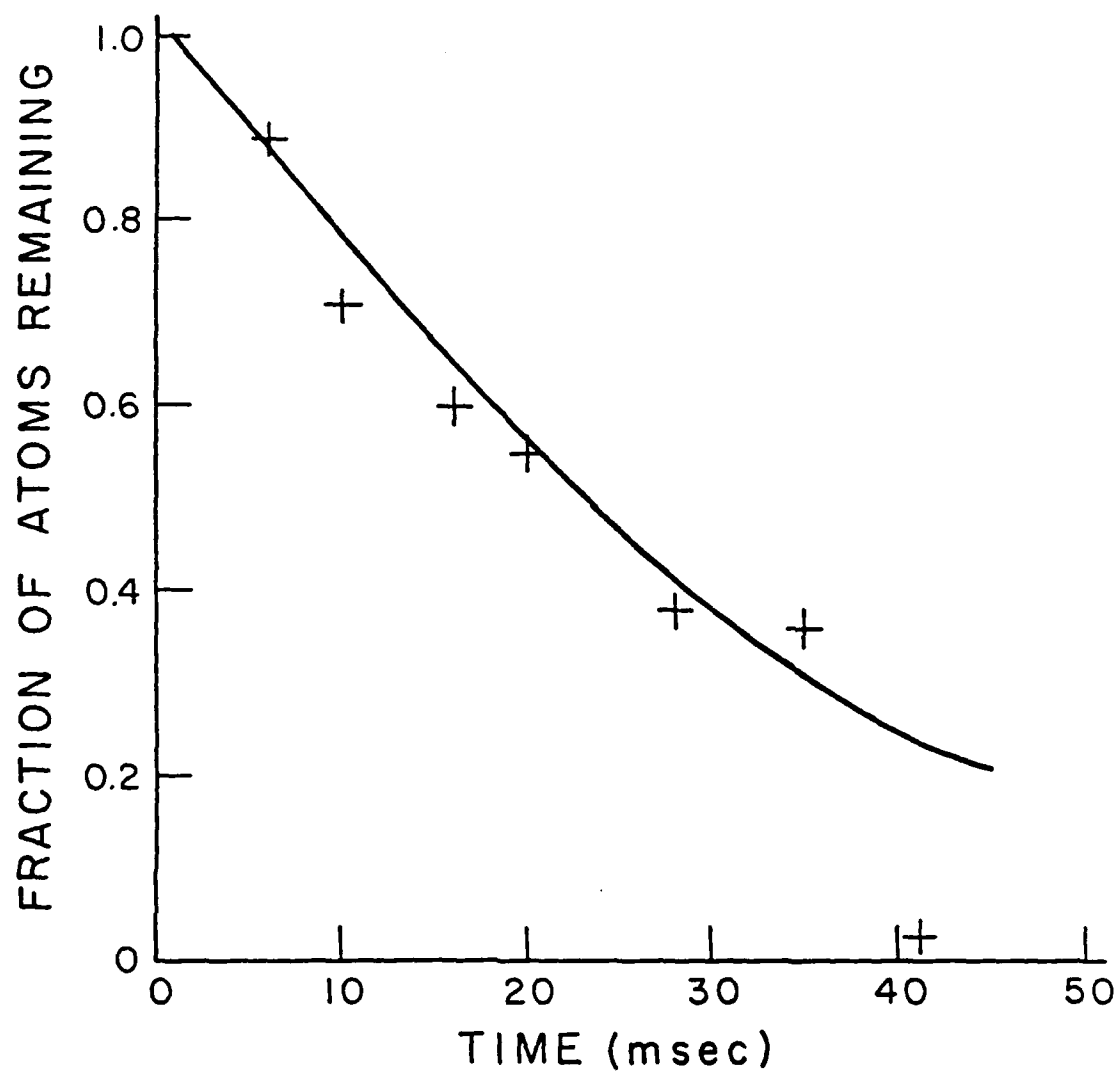fit.

Figure 1

Figure 2

Figure 3